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Model independent constraints on anomalous gauge boson self-couplings from e^+e^- colliders with longitudinally polarized beams

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Abstract

We explore the possibility of deriving model independent limits on the anomalous trilinear electroweak gauge boson couplings from high energy $e^+e^- \to W^+W^-$, by combining the cross sections for the different initial and final states polarizations integrated with suitable kinematical cuts. In the case of the CP conserving couplings the limits can be disentangled, and are given by simple mathematical expressions. Numerical results show the advantages of this approach, in particular the important role of polarization in improving the bounds.

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The precise measurement of the $WW\gamma$ and WWZ couplings is essential for the confirmation of the non abelian gauge structure of the Standard Model (SM). In this regard, a special role is played by the process

$$e^+ + e^- \to W^+ + W^- \tag{1}$$

at the planned high energy e^+e^- colliders, because in this case deviations from the SM are significantly enhanced by increasing the CM energy, and correspondingly the sensitivity is improved. In general, the trilinear gauge boson interaction includes CP violating couplings as well as CP conserving ones. The set of measurements sensitive to the CP violating couplings and their separation was discussed in Ref.[1]. Furthermore, the possibility of separately constraining the C and P violating (but CP conserving) anapole coupling, using process (1) with initial beams longitudinal polarization, was discussed in Ref.[2]. Therefore, we shall limit here to the derivation of constraints for the CP conserving couplings which appear in the effective Lagrangian [3, 4]

$$\begin{aligned}
\mathcal{L}_1 &= -ie\left[A_\mu\left(W^{-\mu\nu}W^+_\nu - W^{+\mu\nu}W^-_\nu\right) + F_{\mu\nu}W^{+\mu}W^{-\nu}\right] - ie\,x_\gamma\,F_{\mu\nu}W^{+\mu}W^{-\nu} \\
&- ie\left(\cot\theta_W + \delta_Z\right)\left[Z_\mu\left(W^{-\mu\nu}W^+_\nu - W^{+\mu\nu}W^-_\nu\right) + Z_{\mu\nu}W^{+\mu}W^{-\nu}\right] \\
&- ie\,x_Z\,Z_{\mu\nu}W^{+\mu}W^{-\nu} + ie\,\frac{y_\gamma}{M_W^2}\,F^{\nu\lambda}W^-_{\lambda\mu}W^{+\mu}_{\ \ \nu} + ie\,\frac{y_Z}{M_W^2}\,Z^{\nu\lambda}W^-_{\lambda\mu}W^{+\mu}_{\ \ \nu}\,,
\end{aligned} \tag{2}$$

where $W^\pm_{\mu\nu} = \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu$ and $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$. According to Eq.(2), in general we have five independent couplings, with SM values $\delta_Z = x_\gamma = x_Z = y_\gamma = y_Z = 0$. Since the unpolarized cross section depends on all coupling constants, it should be difficult to separately constrain them using this observable only. To disentangle and limit the couplings in a model independent way one would need more information. This should be provided by the separate measurements of the cross sections for initial and final states polarizations, which depend on independent combinations of the coupling constants. Ideally, the three possible W^+W^- polarizations (LL, TL and TT), combined with the two longitudinal $e^-\,e^+$ ones (RL and LR) would determine a sufficient set of observable cross sections. The purpose of this note is to illustrate the role of polarizations to derive model independent bounds on the five anomalous couplings and to quantitatively assess the corresponding expected sensitivities.

The basic objects are the deviations of the polarized cross sections from the SM values

$$\Delta\sigma = \sigma - \sigma_{SM}, \tag{3}$$

where, in terms of the Born γ-, Z- and ν-exchange amplitudes and their deviations from the SM expressions due to the anomalous gauge couplings:

$$\begin{aligned}
d\sigma &\propto |\mathcal{A}(\gamma) + \Delta\mathcal{A}(\gamma) + \mathcal{A}(Z) + \Delta\mathcal{A}(Z) + \mathcal{A}_1(\nu)|^2 + |\mathcal{A}_2(\nu)|^2, \\
d\sigma_{SM} &\propto |\mathcal{A}(\gamma) + \mathcal{A}(Z) + \mathcal{A}_1(\nu)|^2 + |\mathcal{A}_2(\nu)|^2.
\end{aligned} \tag{4}$$

In Eq.(4) we have distinguished the ν- exchange amplitudes with $|\lambda-\bar{\lambda}|\leq 1$ and $|\lambda-\bar{\lambda}|=2$, where λ and $\bar{\lambda}$ are the W^- and W^+ helicities. With the aid of explicit formulae for the helicity amplitudes given, *e.g.*, in Ref.[4], one easily finds for the specific initial and final polarizations the following dependence of the amplitudes deviations $\Delta\mathcal{A}$'s in Eq.(4):

$$\begin{aligned}\Delta\mathcal{A}^{ab}_{LL}(\gamma) &\propto x_\gamma \\ \Delta\mathcal{A}^{ab}_{LL}(Z) &\propto \left(x_Z+\delta_Z\frac{3-\beta_W^2}{2}\right) g_e^a,\end{aligned} \tag{5}$$

$$\begin{aligned}\Delta\mathcal{A}^{ab}_{TL}(\gamma) &\propto x_\gamma+y_\gamma \\ \Delta\mathcal{A}^{ab}_{TL}(Z) &\propto (x_Z+y_Z+2\delta_Z)\, g_e^a,\end{aligned} \tag{6}$$

and

$$\begin{aligned}\Delta\mathcal{A}^{ab}_{TT}(\gamma) &\propto y_\gamma \\ \Delta\mathcal{A}^{ab}_{TT}(Z) &\propto \left(y_Z+\delta_Z\frac{1-\beta_W^2}{2}\right) g_e^a.\end{aligned} \tag{7}$$

In Eqs.(5)-(7): $\beta_W=\sqrt{1-4M_W^2/s}$, the lower indices LL, TL and TT refer to the final W^-W^+ polarizations, the upper indices a and b indicate the initial e^- e^+ RL or LR polarizations, and $g_e^R=\tan\theta_W$ and $g_e^L=g_e^R\left(1-1/2\sin^2\theta_W\right)$ are the corresponding electron couplings. One should notice that σ_{LL}, σ_{TL} and σ_{TT} depend on the combinations $(x_\gamma, x_Z+\delta_Z(3-\beta_W^2)/2)$, $(x_\gamma+y_\gamma, x_Z+y_Z+2\delta_Z)$ and $(y_\gamma, y_Z+\delta_Z(1-\beta_W^2)/2)$ respectively.

In order to assess the sensitivity of the different cross sections to the gauge boson couplings, we define a χ^2 function as

$$\chi^2=\left(\frac{\Delta\sigma}{\delta\sigma_{SM}}\right)^2, \tag{8}$$

where $\sigma\equiv\sigma(z_1,z_2)=\int_{z_1}^{z_2}(d\sigma/dz)\,dz$ with $z=\cos\theta$ and $\delta\sigma_{SM}$ is the accuracy experimentally obtainable on $\sigma(z_1,z_2)_{SM}$. Including both statistical and systematical errors, $\delta\sigma_{SM}=\sqrt{(\delta\sigma_{stat})^2+(\delta\sigma_{syst})^2}$, where $(\delta\sigma/\sigma)_{stat}=1/\sqrt{L_{int}\varepsilon_W\sigma_{SM}}$, with L_{int} the integrated luminosity and ε_W the efficiency for W^+W^- reconstruction in the considered polarization state. For that we take the channel of lepton pairs $(e\nu+e\mu)$ plus two hadronic jets, which corresponds to $\varepsilon_W\simeq 0.3$ [5]-[8].[3] Then, as a criterion to derive allowed regions of the coupling constants, we will impose that $\chi^2\leq\chi^2_{crit}$, where χ^2_{crit} is a number which specifies a chosen confidence level and in principle can

[3] Actually, this reconstruction efficiency might be somewhat smaller, depending on the detector [5]. On the other hand, for our estimates we have taken a rather conservative choice for the integrated luminosity, while recent progress in machine design seems to indicate that quite larger values are attainable [7] and can compensate for the reduction of ε_W.

depend on the details of the analysis. In this procedure, an essential role is played by the values of z_1 and z_2. Indeed, for each initial and final polarizations, it is possible to choose the upper and lower integration limits in such a way as to get maximum sensitivity of the corresponding polarized cross sections to the combinations of the coupling constants in Eqs.(5)-(7) [5, 2]. The search of these 'optimal' integration regions can be done numerically, by plotting in each case the χ^2 function (8) *vs.* the anomalous couplings for different z_1 and z_2, and by looking for the values of z_1 and z_2 which minimize the range of couplings such the inequality $\chi^2 \leq \chi^2_{crit}$ holds. To be closer to a possible experimental situation, we have taken into account that in practice the cross section should be

$$\sigma = \frac{1}{4}\left[(1+P_1)\cdot(1-P_2)\,\sigma^{RL} + (1-P_1)\cdot(1+P_2)\,\sigma^{LR}\right], \tag{9}$$

where P_1 (P_2) are less than unity, and represent the actual degrees of longitudinal polarization of e^- (e^+). In the sequel we shall consider as RL or LR the simplified situations $P_1 = -P_2 = P > 0$ and $P_1 = -P_2 = -P$, respectively, with $P = 0.9$ as a possible value [9].

In Fig.1 we show an example relevant to the cross sections for unpolarized W's and both unpolarized and polarized electrons. For simplicity only the coupling x_γ is considered, with all the other ones taken equal to their SM values. The inputs as well as the resulting optimal kinematical regions are presented in the caption of the figure. The allowed limits on the values of x_γ are at the two standard deviations level (or 95% CL), which for our analysis corresponds to $\chi^2_{crit} = 4$. In this example, as well as in the following analysis, we have taken $(\delta\sigma/\sigma)_{syst} = 2\%$ as currently assumed [5]. The role of optimal kinematics and of longitudinal initial polarizations is particularly evident in this particular example. This is connected to the fact that for unpolarized and LR e^-e^+ the relevant angular distribution of $\Delta\sigma$ in the numerator of Eq.(8) has a zero, so that the integration over the whole angular range allowed by an experimental 10° cut ($z_1 = -0.98$, $z_2 = 0.98$) would lead to a reduced signal from the anomalous coupling. Furthermore, the cross section for final TT and unpolarized W^+W^- and any initial polarization includes the contribution of the ν-mediated amplitudes with $\lambda - \bar{\lambda} = \pm 2$ (see Eq.(4)), which by far dominates in the forward direction and thus strongly suppresses the signal.

The general situation regarding the optimal z_1 and z_2 for the various cross sections, and the corresponding statistical uncertainties, is presented in Table 1 for two values of the CM energy and the planned luminosities [7, 10]. It turns out that in all cases one can take for the lower integration limit the minimum allowed value $z_1 = -0.98$. In fact, at this point the relative deviation $\Delta\sigma/\sigma_{SM}$ and $\Delta\sigma/\delta\sigma_{SM}$ are both maximal and correspondingly so is the sensitivity to the anomalous couplings. This reflects the fact that the 'background' ν-exchange contribution to the cross section is minimal in the backward direction. Consequently, the searched for optimal kinematical region can be specified by only $z_{opt} \equiv z_2$.

Applying the procedure outlined above to the reaction $e^-e^+ \to W^-_L W^+_L$, and taking into account the results of Table 1, we obtain the $\chi^2 = 4$ contours allowed

	$e^-_R e^+_L \to W^-_L W^+_L$	$e^-_R e^+_L \to W^-_L W^+_T + W^-_T W^+_L$	$e^-_R e^+_L \to W^-_T W^+_T$
z_{opt}	0.98 (0.98)	0.98 (0.98)	0.22 (0.22)
$\sigma_{SM}(fb)$	76 (19)	28 (1.9)	2.9 (0.6)
$\delta_{stat}(\%)$	4.7 (5.9)	7.6 (18.6)	24 (32)
	$e^-_L e^+_R \to W^-_L W^+_L$	$e^-_L e^+_R \to W^-_L W^+_T + W^-_T W^+_L$	$e^-_L e^+_R \to W^-_T W^+_T$
z_{opt}	0.85 (0.96)	−0.35 (0.98)	0.13 (0.13)
$\sigma_{SM}(fb)$	342 (87)	44 (35)	780 (187)
$\delta_{stat}(\%)$	2.2 (2.8)	6.2 (4.4)	1.5 (1.9)

Table 1: Optimal integration regions for $E_{CM} = 0.5\,TeV$ and $1\,TeV$ (in parentheses). Integrated luminosities $L_{int} = 20\,fb^{-1}$ and $50\,fb^{-1}$ respectively; $P_1 = -P_2 = 0.9$ (RL), $P_1 = -P_2 = -0.9$ (LR).

to the combinations of couplings of Eq.(5) by each initial polarization. These are represented for $E_{CM} = 500\,GeV$ in Fig.2. The allowed regions enclosed by those contours are all elliptical (the RL and LR ones are extremely flattened, depending on P_1 and P_2, and therefore only their parts relevant to the intersections are drawn in Fig.2). Of the four common intersections, whose existence for RL and LR initial polarizations is assured by $g_e^L \simeq -g_e^R$, only one includes the region around the SM values of the trilinear gauge boson couplings. One finds analytically that the position of the intersections does not depend on the polarizations P_1 and P_2, so that the only way to exclude the three intersections not containing the SM point would be to change the CM energy.

Concentrating on the region around the origin, in Fig.3 we represent a magnification of Fig.2 and the area allowed by the combination of the two observables σ^{RL} and σ^{LR}, taking $\chi^2_{crit} = 5.9$ and $E_{CM} = 500\,GeV$ (the smaller region would be the result for $E_{CM} = 1\,TeV$). The area allowed by the unpolarized cross section does not add any significant information, and is included in the figure just for comparison.

From Fig.3 one can read the constraints, which can be expressed by the following inequalities:

$$-\alpha_1^{LL} < x_\gamma < \alpha_2^{LL}, \tag{10}$$

$$-\beta_1^{LL} < x_Z + \delta_Z \frac{3-\beta_W^2}{2} < \beta_2^{LL}, \tag{11}$$

where $\alpha_{1,2}^{LL}$ and $\beta_{1,2}^{LL}$ are the projections of the combined allowed area on the horizontal and vertical axes, respectively, and clearly depend on the inputs for energy, polarization, kinematics and luminosity. One can notice that in the process $e^+e^- \to W_L^+ W_L^-$ the initial state polarization allows to bound x_γ separately. The typical bounds for the inputs in the caption of Table 1 are of the order of 10^{-3}, as can be seen from Fig.3. This order of magnitude is simply explained by considering, *e.g.*, the amplitude relevant to σ_{LL}^{RL}:

$$\mathcal{A}_{LL}^{RL} = \frac{s}{M_W^2}\left[\frac{3-\beta_W^2}{2}\left(1 - \chi_Z\,\cot\theta_W g_e^R\right) + x_\gamma - \chi_Z\, g_e^R\,\left(x_Z + \delta_Z \frac{3-\beta_W^2}{2}\right)\right], \tag{12}$$

where $\chi_Z = s/\left(s - M_Z^2\right)$ is the Z boson propagator. The cross section is given by

$$\frac{d\sigma_{LL}^{RL}}{dz} = \frac{\pi\alpha_{e.m.}^2\beta_W^3}{8s}\left(1 - z^2\right)|\mathcal{A}_{LL}^{RL}|^2. \tag{13}$$

From the requirement $\chi^2 \leq \chi^2_{crit} = 4$ one has for $x_Z = \delta_Z = 0$:

$$|x_\gamma| \leq \frac{1}{4}\sqrt{\chi^2_{crit}}\left(3 - \beta_W^2\right)\left(1 - \chi_Z\right)\left(\frac{\delta\sigma_{SM}}{\sigma_{SM}}\right). \tag{14}$$

From Table 1 and the assumed 2% systematic error we have $(\delta\sigma_{SM}/\sigma_{SM}) \simeq 5\%$ and from (14): $|x_\gamma| \leq 1.8 \times 10^{-3}$.

We now turn to the other polarized cross section, and repeat the same analysis there. In Fig.4 we represent the analogous of Fig.3 for the combinations of coupling constants in Eq.(6), which results from $e^+e^- \to W_T^+W_L^- + W_L^+W_T^-$. In this case, one obtains the following inequalities, analogous to (10) and (11):

$$-\alpha_1^{TL} < x_\gamma + y_\gamma < \alpha_2^{TL}, \tag{15}$$

$$-\beta_1^{TL} < x_Z + y_Z + 2\delta_Z < \beta_2^{TL}. \tag{16}$$

Finally, from $e^+e^- \to W_T^+W_T^-$ one obtains for the combinations of Eq.(7) the allowed regions in Fig.5 and the corresponding inequalities:

$$-\alpha_1^{TT} < y_\gamma < \alpha_2^{TT}, \tag{17}$$

$$-\beta_1^{TT} < y_Z + \frac{1-\beta_W^2}{2}\delta_Z < \beta_2^{TT}. \tag{18}$$

The less restrictive limits in Fig.5 are determined by the larger width of the region enclosed by the LR contours, mainly due to the dominance in this channel of the $|\lambda - \bar{\lambda}| = 2$ contribution which significantly reduces the sensitivity even in the optimal kinematical region. Also, we can notice that with initial state polarization $e^+e^- \to W_T^+W_T^-$ can constrain y_γ separately.

Finally, from Eqs.(10) to (18) one can obtain the simple, model independent and separate bounds:

$$-\frac{1}{\beta_W^2}B_2 < \delta_Z < \frac{1}{\beta_W^2}B_1, \tag{19}$$

$$-\left(\beta_1^{LL} + \frac{3-\beta_W^2}{2\beta_W^2}B_1\right) < x_Z < \beta_2^{LL} + \frac{3-\beta_W^2}{2\beta_W^2}B_2, \tag{20}$$

$$-\left(\beta_1^{TT} + \frac{1-\beta_W^2}{2\beta_W^2}B_1\right) < y_Z < \beta_2^{TT} + \frac{1-\beta_W^2}{2\beta_W^2}B_2, \tag{21}$$

where $B_1 = \beta_1^{LL} + \beta_1^{TT} + \beta_2^{TL}$ and $B_2 = \beta_2^{LL} + \beta_2^{TT} + \beta_1^{TL}$. These constraints should be joined with (10) and (17) for x_γ and y_γ, respectively.

$E_{CM}(TeV)$	$x_\gamma\,(10^{-3})$	$y_\gamma\,(10^{-3})$	$\delta_Z\,(10^{-3})$	$x_Z\,(10^{-3})$	$y_Z\,(10^{-3})$
0.5	$-1.8 \div 1.8$	$-8.6 \div 9.2$	$-40 \div 40$	$-45 \div 45$	$-22 \div 22$
1	$-0.5 \div 0.5$	$-3.0 \div 3.0$	$-13 \div 13$	$-14 \div 14$	$-5.7 \div 6.0$

Table 2: Model independent limits on the non-standard gauge boson couplings at the 95% CL. Same inputs as in Table 1.

We have one more constraint from the combination of inequalities (10) and (15):

$$-\left(\alpha_1^{TL}+\alpha_2^{LL}\right) < y_\gamma < \alpha_1^{LL}+\alpha_2^{TL}, \tag{22}$$

which has to be compared with (17). It turns out that for $E_{CM}=500\,GeV$ the most stringent limitation for y_γ is determined by (22), whereas (17) is the most restrictive one for $1\,TeV$.

The numerical results from these relations, and the chosen inputs for the luminosity and the initial polarization, are collected in Table 2.

It should be interesting to specialize the previous analysis to 'physically' motivated models, where nonstandard trilinear gauge boson couplings originate from some new interaction acting at a higher scale Λ much greater than the Fermi scale. A popular class of models assumes for such an interaction an $SU(2)\times U(1)$ spontaneously broken local symmetry, with gauge bosons γ, W and Z and one Higgs doublet [11]–[13]. Accordingly, the weak interaction Lagrangian should be given by the combination

$$\mathcal{L}_W=\mathcal{L}_{SM}+\sum_d\sum_k\frac{f_k^{(d)}}{\Lambda^{d-4}}\mathcal{O}_k^{(d)}, \tag{23}$$

where $\mathcal{L}_{SM}$ is the familiar, renormalizable SM Lagrangian, and the gauge invariant effective operators $\mathcal{O}_k^{(d)}$ are ordered by dimension d and represent the low energy effect of the new interaction, giving rise in particular to the anomalous gauge boson couplings. From the good agreement of the measured fermion couplings with the SM ones, one assumes that new contributions to these couplings can be neglected. Then, limiting to dimension 6 operators, the relevant C and P conserving operators are [14]

$$\begin{aligned}
\mathcal{O}_{WWW}^{(6)} &= Tr\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}_\rho^{\mu}\right],\\
\mathcal{O}_{W}^{(6)} &= \left(D_\mu\Phi\right)^\dagger\hat{W}^{\mu\nu}\left(D_\nu\Phi\right),\\
\mathcal{O}_{B}^{(6)} &= \left(D_\mu\Phi\right)^\dagger\hat{B}^{\mu\nu}\left(D_\nu\Phi\right).
\end{aligned} \tag{24}$$

Here, Φ is the Higgs doublet and, in terms of the B and W field strengths: $\hat{B}^{\mu\nu}=i(g'/2)B^{\mu\nu}$, $\hat{W}^{\mu\nu}=i(g/2)\vec{\tau}\cdot\vec{W}^{\mu\nu}$ with $\vec{\tau}$ the Pauli matrices. The contributions to the anomalous vector boson couplings are:

$$x_\gamma=\cos^2\theta_W\,\left(f_B^{(6)}+f_W^{(6)}\right)\frac{M_Z^2}{2\Lambda^2};\qquad y_\gamma=f_{WWW}^{(6)}\,\frac{3M_W^2g^2}{2\Lambda^2}; \tag{25}$$

$E_{CM}(TeV)$	$x_\gamma\,(10^{-3})$	$y_\gamma\,(10^{-3})$	$\delta_Z\,(10^{-3})$	$x_Z\,(10^{-3})$	$y_Z\,(10^{-3})$
0.5	$-1.8 \div 1.8$	$-8.6 \div 9.2$	$-3.7 \div 3.7$	$-1.0 \div 1.0$	$-16 \div 17$
1	$-0.5 \div 0.5$	$-3.0 \div 3.0$	$-1.0 \div 1.0$	$-0.3 \div 0.3$	$-5.5 \div 5.5$

Table 3: 95% CL limits for the model with three independent anomalous couplings. Same inputs as in Table 1.

$$\delta_Z = \cot\theta_W\, f_W^{(6)}\,\frac{M_Z^2}{2\Lambda^2}; \quad x_Z = -\tan\theta_W\, x_\gamma; \quad y_Z = \cot\theta_W\, y_\gamma. \tag{26}$$

According to (25) and (26), in this model there are only three independent couplings which we can choose to be x_γ, y_γ and δ_Z.[4] Of these, x_γ and y_γ are directly bound from Table 2, and the constraints on x_Z and y_Z are simply obtained from the previous ones using last two relations of Eq.(26). Finally, the bound on δ_Z is obtained by combining that on x_Z with Eq.(11). This procedure gives the tightest bounds on δ_Z: the other ones, utilizing the inequalities (16) or (18) would be less stringent. This is due to the fact that the regions allowed by the $W_L^+W_L^-$ production cross sections are much more restricted than those determined by the other final polarizations, as can be seen by comparing Figs. 3 to 5. Numerically, we find the values reported in Table 3, to be compared with the model independent ones in Table 2.

In conclusion, summarizing the previous analysis, the results obtained show the potential of the approach to derive bounds on the anomalous trilinear boson couplings, based on cross sections integrated with suitably defined cuts and combinations of all possible initial and final polarizations. This allows to separately constrain the CP conserving couplings in a model independent way with high sensitivity, typically of the order of $10^{-3} - 10^{-2}$ at $E_{CM} = 0.5\,TeV$. Particularly stringent bounds can be expected for dynamical models beyond the SM with reduced number of independent couplings.

In principle, one could include in this kind of analysis also the anomalous coupling δ_γ, still CP conserving, which would be induced *e.g.* by a dimension 8 contribution to (23) [13]. Having, in this case, equal numbers of polarized observables and anomalous couplings, separate constraints could still be found.

The bounds derived above are approaching the order of magnitude of the radiative corrections to the SM couplings [16]. Thus, the next step should be the combination in the fitting procedure of the SM radiative corrections with the anomalous gauge boson couplings.

[4] As mentioned in [11], the correlations between different anomalous trilinear gauge boson couplings exhibited in Eqs.(25) and (26) are due to the truncation of the effective Lagrangian (23) at the dimension 6 level, and do not hold any longer when dimension 8 (or higher) operators are included. It is interesting to notice that the relation between x_γ and x_Z in (26) was first introduced in [15] on the basis of global $SU(2)_W$ symmetry for W dynamics and $W_3 - \gamma$ mixing.

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Figure captions

Fig.1 x_γ-dependence of the χ^2 in Eq.(8) for $e^+e^- \to W^+W^-$ at $E_{CM} = 500\, GeV$, integrated luminosity $L_{int} = 20\, fb^{-1}$. 'unpol' and 'unpol-opt' refer to the unpolarized cross section integrated over the angular range $|z| < 0.98$ and over the 'optimal' kinematical region $(-0.98 \div 0.0)$, respectively. 'LR' and 'RL' refer to polarized cross sections integrated up to $z_{opt} = -0.2$ and $z_{opt} = 0.7$, respectively.

Fig.2 Allowed domains (95% C.L.) from $e^-e^+ \to W_L^- W_L^+$ with polarized $(RL,\, LR)$ and unpolarized initial beams at $E_{CM} = 0.5\, TeV$, inputs as specified in Table 1.

Fig.3 Same as Fig.2, magnified allowed domain around the origin, and combined area allowed by RL and LR cross sections. The smaller area around origin refers to $E_{CM} = 1\, TeV$, $L_{int} = 50\, fb^{-1}$.

Fig.4 Allowed domains (95% C.L.) for $(x_\gamma + y_\gamma,\, x_Z + y_Z + 2\delta_Z)$ from $e^-e^+ \to W_L^- W_T^+ + W_T^- W_L^+$ with same inputs as in Fig.2 and Fig.3.

Fig.5 Allowed domains (95% C.L.) for $(y_\gamma,\, y_Z + \delta_Z \frac{1-\beta_W^2}{2})$ from $e^-e^+ \to W_T^- W_T^+$ with same inputs as in Fig.2 and Fig.3.